

Lessons from a Dam Failure¹

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ABSTRACT. The IVEX Dam (Chagrin River, northeastern Ohio) failed catastrophically on 13 August 1994, releasing 38,000 m³ (about 10 million gallons) of impounded water and sediment. This event was triggered by a 70-year rainfall event (13.54 cm of rainfall within 24-hours), resulting in flows 1.9 m above the top of the spillway and impinging on the top of the dam. The failure was the result of seepage piping at the toe of the dam, near the masonry spillway-earthen dam contact. Eyewitnesses reported that collapse of the seepage pipe created a breach in the dam that rapidly downcut. Paleohydrologic modeling suggests peak discharge through the breach was about 466 m³sec⁻¹, substantially dewatering the reservoir in approximately 2-3 minutes.

The effects of failure included erosion, flooding, and sedimentation downstream, and erosion of fine-grained sediment within the reservoir itself. Of the accumulated reservoir sediment, 9-13% was mobilized by dam breach and consequent incision (as the Chagrin River re-established its gradient by downcutting through reservoir sediment). Of this amount, 61-86% was trapped in a downstream reservoir (threatening the integrity of this structure).

The failure of this dam can be attributed to a large hydrologic event and the combination of several factors: 1) inadequate spillway design, 2) lack of an emergency spillway, 3) 86% loss of permanent pool capacity due to 152 years of sedimentation, and 4) poor dam maintenance resulting in seepage piping failure. Similar dam failures will become an increasing societal problem, due to the aging of the nation's 75,591 larger dams and reservoirs, of which 95% are privately owned and operated.

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INTRODUCTION

It is well known that construction of a dam and reservoir on a river will cause significant changes in the hydrology, sedimentology, and ecology of that fluvial system (Gottschalk 1964; Baxter 1977; Petts 1977; Simons 1979; Cooke and others 1993). There are 75,591 dams in the United States taller than about 7.6 m, or impounding more than 61,650 m³ (Costa 1988; FEMA 1999). Although the public tends to think of the huge federal projects in western US as examples of dams, in fact 95% of the dams in the US are smaller structures that are privately owned and operated.

Dams are constructed for specific purposes, such as hydropower, hydroelectric power, navigation, flood control, water source, or recreation. In some cases multiple use is possible, but not all uses are compatible. For example, locks and dams for navigation purposes are managed for constant pool elevations, while water source reservoirs are managed to maximize pool height, but flood control structures are managed to minimize pool heights (in order to accommodate flood storage). Many of the nation's older dams and reservoirs have changed in their primary purpose over time, commonly a change from hydropower to other uses.

Dams and reservoirs create liabilities as well as benefits. Earthquakes, floods, landslides, and volcanic activity have resulted in catastrophic dam failures in a variety of environments (Gupta and Rastogi 1976). In the US, 318 people have been killed by dam failures between 1960-

1997 (FEMA 1999). In other instances, reservoirs such as Lake Nasser (behind the Aswan High Dam on the Nile River) have resulted in evaporative water loss, salinization, loss to groundwater recharge, and the spread of human disease via vectors that established habitat in the reservoir (Waddy 1975).

Aside from such dramatic examples of liabilities, often the most significant problems are incremental, resulting from changes in sediment budgets (Gottschalk 1964; McHenry 1974; Baxter 1977; Petts 1984; Ford 1990; Thornton 1990). It is a well-documented geomorphological concept that dams and reservoirs create a temporary baselevel for the fluvial system (Leopold 1956; Leopold and others 1964). This change in the longitudinal profile of the stream gradient results in the deposition of bedload as a delta that progrades across the reservoir, and in the deposition of a significant portion of the suspended load as fine-grained sediments which settle in the distal portion of the reservoir (Gottschalk 1964; Petts 1984; Cogollo and Villela 1988). Bed and bank erosion downstream of the dam is a natural consequence of the stream adjusting to steepened gradients and low initial sediment load after exiting the reservoir (Gregory and Park 1974; Dolan and others 1974; Simons 1979; Andrews 1986). Flow regulation and changes in sediment loads in the reservoir and downstream can have biological effects (changing substrate in critical fisheries habitat and growth of plankton in the reservoir) and chemical effects (changing nutrient loads, dissolved oxygen content, and temperature of the water) which jointly affect stream ecosystems (Dolan and others 1974; Baxter 1977; Sale and others

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1982; Petts 1984; Carling 1995; Wilcock and others 1996).

As reservoir sedimentation occurs, the storage capacity of the reservoir declines. Depending on its outflow type, many reservoirs can be subdivided into permanent pool storage (the reservoir volume below the spillway elevation) and flood storage (the reservoir volume between spillway elevation and the top of the dam). Sedimentation results in loss of permanent pool storage. The ability of a reservoir to attenuate (delay and reduce the magnitude of) a floodwave is a function of storage volume and of inflow-outflow relationships (for example, Haan and others 1994).

If a dam has an adequate spillway design to safely handle the "Probable Maximum Flood" (PMF), as determined by hydrograph records or by hydrologic models, then loss of storage capacity should not directly impact the safety of the structure. This is true of recently constructed dams, which also usually incorporate an emergency spillway design into the structure as additional protection against failure.

However, many of the older dams in the US predate these types of hydrologic design. In such cases, the worse case scenario is a situation where inflow greatly exceeds outflow (inadequate spillway design) and there is no emergency spillway. In this worse case scenario, pool stage height in the reservoir could rise to the point of overtopping the dam, or causing such elevated hydrostatic pressures as to facilitate seepage piping failure. In such cases, the safety of the structure depends entirely on attenuation of the floodwave by storage within the reservoir. Storage capacity loss is a long-term progressive process, in the absence of sediment management, making the dam increasingly vulnerable to failure during a high-magnitude flood event. Big Tujunga dam in southern California lost 70% of its storage capacity over a four year interval, due to heavy sediment loads, with the consequence that floodwaves now pass across the spillway only slightly attenuated by the reservoir (Scott 1973). In smaller reservoirs in the Garza-Little Elm basin of Texas, storage capacity loss has reduced attenuation from 10% to less than 1% (Gilbert and Sauer 1970). During Tropical Storm Alberto (July 1994), over 200 dams failed in Georgia as a consequence of the processes discussed here (FEMA 1999).

Loss of storage capacity also affects other uses for the reservoir (for hydroelectric power, navigation, water storage, fisheries, or recreation). Such loss can be mitigated in several ways. One way is to over-design the size of the reservoir, so that years are added to the life of the structure. A second solution is clever hydrologic design to minimize the trapping efficiency of the structure, utilizing the reservoir size, shape, depth, internal circulation, and sluicing of bottom water through the dam (Brune 1953; Haan and others 1994). A third solution is to dredge the reservoir at various times, but this can be costly, especially if the sediments are contaminated with pesticide residues or heavy metals requiring special disposal (Cooke and others 1993).

According to recent surveys, there are about 9,200 dams in the US classed as high hazard, because of the inadequate spillway design, lack of emergency spillways,

and absence of sediment management. About 35% of these dams have not had safety inspections in over 10 years (FEMA 1999). The IVEX dam was one such example—over its 152-year history sediment accumulated unchecked, thus there had been 86% permanent pool storage capacity loss by 1994, when the dam failed during a significant flood. Whereas other studies have focused on the environmental impacts of constructing and maintaining dams, the purpose of this report is to evaluate the effects of dam failure, in what may become a common scenario as the nation's dams age.

BACKGROUND

Hydrology and Geology

The IVEX dam is located near the Village of Chagrin Falls, on the Chagrin River, in northeast Ohio (Fig. 1). The Chagrin River has a total drainage area of 428 km², of which 87.7 km² is located upstream of the IVEX reservoir. The Chagrin River basin is part of the Allegheny Plateau, and has maximum dimensions 48 km north-south by 27 km east-west. The river has two major tributaries (the Aurora Branch and East Branch) which join the main river downstream of the dam. Total stream length is 79 km, and the dam is located at river kilometer (RK) 48.75. Downstream flood records are available from the USGS gaging station at Willoughby (RK 8) for the interval 1925-present. Between 1925-1994, the mean annual discharge was 103 m³sec⁻¹, while the highest recorded flow (22 March 1948) was 3750 m³sec⁻¹ (ODNR 1987; USGS 1994).

The Chagrin River is a dendritic, meandering stream that is partly entrenched into bedrock, with a maximum incision of 90 m deep and 0.8 km wide. Floodplains have a narrow width, being only 1.8 km at RK 3, 360 m at RK 8, and virtually nonexistent upstream except in meander loops or at the junction of tributaries. The overall river slope is 3.0 m/km, having numerous small falls and rapids in its upper part. The drainage basin geology is dominated by Devonian- and Mississippian-age siliciclastic sedimentary rocks mantled by Illinoian- and Wisconsin-age glacial deposits (Banks and Feldman 1970; White 1982). Stream channel and bank sediments are dominated by sand and gravel. Given the relatively steep gradients, relatively narrow and thin floodplains, and coarse-grained stream substrates, it is inferred that fine-grained sediments are transported through the Chagrin River system, unless they are trapped behind a dam.

History of the Dam

The IVEX dam was constructed in 1842, shortly after the immediate region was developed by European settlers. The Village of Chagrin Falls was established here in 1833 primarily for its hydropower potential. Numerous small wooden dams were eventually consolidated into two larger dams with masonry construction: the Lower Mill Pond dam and the Upper Mill Pond (IVEX) dam (Blakeslee 1874). A review of historical land-use changes in the drainage basin, and the resulting impact on soil erosion loss and sediment yield, is given elsewhere (Evans and others 2000a).

The IVEX dam has partially or completely failed five

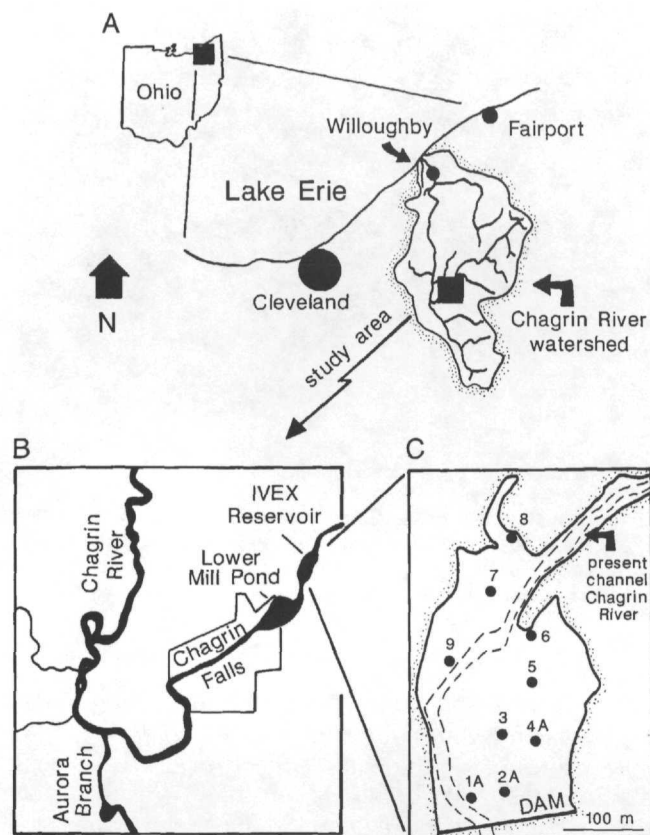


FIGURE 1. Map showing A) location of the Chagrin River and study area in northeastern Ohio, B) location of the Lower Mill Pond and Upper Mill Pond (IVEX Reservoir) near the Village of Chagrin Falls, and C) locations of sediment cores in the IVEX Reservoir, and new path of the incised Chagrin River through the former reservoir.

times during its 152-year life history. Constructed as a spar dam in 1842, unanchored to bedrock, it suffered catastrophic toppling failure that same year. Rebuilt immediately, the structure evolved into a masonry spillway 7.4 m tall, 33 m wide, and 1.0 m thick (Fig. 2), which was attached to bedrock on the west side, and to a 152 m long earth-fill dam on the east side. The dam failed completely in 1877, dewatering the reservoir. Because the owner could not afford to repair it, the reservoir became pasture land until 1890, when repairs were completed, and the reservoir reflooded. The IVEX dam suffered partial failures in 1913 and 1985, due to seepage piping at the masonry spillway-dam contact. Neither of these failures completely dewatered the reservoir. The 1985 failure was patched with hydraulic cement (ODNR 1987).

Neither of these dams were constructed with emergency spillways. Both were listed as "Class 1 Dams" by the Ohio Department of Natural Resources (ODNR), indicating large dams (storage capacity >5000 acre-ft or height >60 ft) where failure could result in loss of life, health hazard, or serious property damage (Ohio Revised Code, Section 1521). Federal authority over the safety of privately owned dams has grown from safety inspections during the 1970s by the US Army Corps of Engineers (under authority of Public Laws 92-366 and 99-662), to the establishment of the 1996 National Dam

Safety Program (P.L. 104-303, Section 215). The National Dam Safety Program is administered by the Federal Emergency Management Agency (FEMA), and involves standardized guidelines for federal dams, grant assistance to states to train private dam owners or operators, and a National Dam Safety Review Board to monitor federal and state efforts.



FIGURE 2. Oldest available photograph of the IVEX dam (about 1870) showing the masonry spillway attached to bedrock on the west bank (left) and the earth-fill dam on the east bank (right). Note absence of trees on the earth-fill dam. The spillway is 7.4 m tall. Photo courtesy of the Chagrin Falls Historical Society.

In the case of these two dams, the safety inspections were conducted by the ODNR Division of Water in 1987. At that time, inspectors were critical of the IVEX dam, requiring the owners to provide a spillway capable of passing the PMF of $1640 \text{ m}^3\text{sec}^{-1}$, repair seepage piping problems, and remove trees from the earth-fill dam. The PMF discharge was calculated from flood routing, using the HEC-1 hydrologic model, for a 100-year rainfall event based upon National Weather Service data (for example, Huff and Angel 1992). IVEX Corporation submitted a plan to undertake remedial actions, which was approved by both DNR Division of Water and the Army Corps of Engineers, on 23 August 1991. However, IVEX Corporation then balked at the cost and considered selling the property, thus delaying implementation of repairs (Baka 1994). None of the required actions had been taken when the dam failed on 13 August 1994.

MATERIALS AND METHODS

Methods used in this study included field examination of erosional and depositional features, surveying, evaluation of the stratigraphy of stream cutbanks and trenches, and collection of nine 8.0-cm diameter vibrocores up to 4.5 m long (see Fig. 1C for core locations). The cores were split in the laboratory, and one half archived. The working half was described, photographed, and sampled for composition, texture, porosity, bulk density, and geochemical analyses (Gill 1996). Most of

the core data is presented elsewhere (Evans and others 2000a). Field transects were used for aid in correlation between cores, to evaluate certain depositional or erosional structures, and to locate historical artifacts used to calibrate age relationships.

One core (94-IVEX-1A) was selected for ^{210}Pb and ^{137}Cs analysis. Twenty-five samples 1-cm thick were taken from this core to identify peak concentrations of ^{137}Cs , which is a bomb-fallout isotope with a 30.2 year half-life. Because ^{137}Cs does not occur naturally, known changes in input rates (due to varying numbers of open-air nuclear tests) can be used to establish the age of various layers in the sediment. For example peak ^{137}Cs values occurred in 1963-1964, prior to implementation of the Limited Test Ban Treaty. ^{137}Cs is strongly adsorbed to clays, and has been used to calculate soil erosion and sediment accumulation in drainage basins (Pennington and others 1973; Ritchie and others 1973; Ritchie and others 1975; Oldfield and others 1980; Campbell and others 1982, 1988; McCall and others 1984; Walling and Bradley 1988; Ritchie and McHenry 1990). ^{210}Pb is a naturally occurring, daughter product of ^{222}Rn , and is deposited above land surfaces at an approximately constant rate by dry fallout. Strongly adsorbed to clays or organics, ^{210}Pb is transported to lakes and reservoirs along with the sediment load. Once deposited in the lake or reservoir, ^{210}Pb decays with a 22.3 year half-life, permitting calculation of sediment rates and ages of sediment horizons over the past 150 years (Goldberg 1963; Koide and others 1972; Robbins and Edgington 1975; Robbins 1978; Krishnaswamy and Lal 1978; Evans and others 1981). Unfortunately, ^{210}Pb geochronology had limited geochronology value in this study because of large variations in the rate of supply, which violate assumptions used for dating purposes (Appleby and Oldfield 1978). The causes for such variations are changes in sediment inputs, as might be expected in a small drainage basin with episodic flood events (for example, Bloesch and Evans 1982; Binford and Brenner 1986). ^{210}Pb was useful for confirming the age of the oldest reservoir sediments, among other things, as discussed more fully elsewhere (Evans and others 2000a). The activities of ^{137}Cs and ^{210}Pb were determined using low-background, high-purity, germanium gamma-counting procedures (EPRI 1996) following Gottgens and others (1999).

RESULTS

Causes and Characteristics of the Dam Failure

On 13 August 1994 the upper Chagrin River watershed experienced 13.54 cm of rainfall within a 24-hour period, which represents approximately a 70-year rainfall event based upon National Weather Service data (Huff and Angel 1992). Prior to failure, flows rose to 1.9 m above the base of the spillway, impinging on the top of the dam (Larry Rohman, IVEX Corporation, written communication to the ODNR 1994). Eyewitnesses on the west bank (spillway side of the dam) took a photograph of the spillway at full flood stage (Fig. 3) just before failure. Note the presence of logs in the tailrace of the spillway. It is possible that logs partially obstructed



FIGURE 3. Photograph of the spillway of the IVEX dam minutes before failure of the dam at the spillway-dam contact (right). Note the growth of trees on the earth-fill dam. Also note presence of logs in the tailrace of the spillway. Photo courtesy of Y. Rausch, Chagrin Falls Historical Society.

the spillway, backing up flow and increasing stage height, at some critical time prior to failure.

Eyewitnesses on the east bank of the earth-fill dam reported seeing active gullying on the downstream toe prior to failure (Randall James, Ohio State University Agricultural Extension Service, verbal communication, 1999). The origin of these gullies would be the result of seepage piping, which is sediment erosion due to the discharge of groundwater. Seepage is a common engineering problem of dams and other hydraulic structures, and is a function of hydraulic head (reservoir pool height). In this case, as the reservoir approached maximum capacity at flood stage, maximum rates of seepage would be expected to occur. Piping (sediment erosion) is also a function of hydraulic gradient, and will occur wherever the upward directed seepage force exceeds the gravity force (Freeze and Cherry 1979; Haan and others 1994). Piping can be significant in situations where drainage pathways exist, such as burrows, cracks, fractures, and root molds, or where discontinuities exist, such as impermeable horizons (Dunne 1990). It is highly probable (although it can not be proven) that seepage piping was concentrated and more effective in this case because of the presence of large trees on the dam. Tree roots and root mold cavities were observed in the breach of the earth-fill dam after the failure took place.

The IVEX failure resembled other seepage piping failures. Commonly, the result of seepage piping is eventual collapse of the pipe, leading to sudden collapse of a portion of the crest of the dam and formation of a breach (for example, MacDonald and Langridge-Monopolis 1984). The breach permits escape of the impounded water, which then downcuts to deepen and widen the breach, thus accelerating the flow rate. In this case, the breach formed near the contact of the masonry spillway and earth-fill dam (Fig. 4). This was the site of previous seepage piping problems, and the breach exposed the hydraulic patch used to repair the 1985 partial dam failure (Fig. 5).



FIGURE 4. Photograph of the breach in the dam taken days after the failure. Note the masonry spillway (left) and earth-fill dam (right). The hydraulic patch from the 1985 seepage piping failure is exposed on the left (west) side of the breach. Also note the reservoir sediments about 4.5 m thick just behind the spillway.

Paleohydrologic modeling of peak discharge in dam failures is notoriously difficult and inaccurate, given transient flow conditions and the inability to measure certain parameters. Improvements to these models have included a more theoretical approach stressing relationships between dimensionless parameters for peak discharge, reservoir drainage, breach formation, and other factors (for example, Walder and O'Connor 1997). In this case, our surveys allowed calculation of the volume of water flowing through the breach ($V_o = 38,000 \text{ m}^3$), the breach dimensions (being a trapezoid 12.4 m wide at the base, 20.0 m wide at the top, and 7.5 m tall), and the erosion rate of breach formation (a conservative estimate from eyewitness accounts is $k = 15 \text{ m hr}^{-1}$). Using the methods of Walder and O'Connor (1997), two dimensionless parameters can be calculated, dimensionless parameter $h = 2.7$, and the dimensionless peak discharge $Q_p^* = 1.2$. Solving the relevant equations



FIGURE 5. Close-up of the breach, showing the 1985 hydraulic patch and plug. Note gullying in the exposed reservoir sediments to the right background.

for these dimensionless values allows calculation of peak discharge through the breach of $Q_p = 466 \text{ m}^3 \text{ sec}^{-1}$. The reservoir was substantially dewatered (this ignores stream discharge that continued to enter the reservoir from upstream) in a time range equal to $2V_o/Q_p$, or about 2.72 minutes. These values are reasonably equivalent to the small number of well documented failures in reservoirs of similar size (Walder and O'Connor 1997).

Downstream Effects

Downstream effects due to the dam failure included flooding, hydraulic damage (erosion), and sedimentation. Immediately downstream of the breach was a wide debris fan (Fig. 6) that extended over 1 km downstream into the reservoir of the Lower Mill Pond. Flood debris suggested that the height of the floodwave was approximately 1.5 m above bankfull depth (about 0.5 m), at a point about 200 m downstream of the spillway. The floodwave crossed the Lower Mill Pond (note, the entire length of this dam is a masonry spillway), and continued downstream. Extensive erosional damage was done to stream banks and culverts, and the causeway of the State Route 87 was inundated at a point about 7.0 km downstream of the breach. Note that most of the damage (for example, streambank erosion and deposition) is not easily quantifiable.



FIGURE 6. View downstream from the IVEX dam showing the debris-fan, bank erosion, and undercutting of mature trees resulting from the dam failure. The Chagrin River meanders to the right in this photo, and the flow crossed old chute channels on that point bar surface.

The Ohio Geological Survey's inspection of the IVEX reservoir following the dam failure revealed that the structure trapped about 236,000 m^3 of fine-grained sediment during its 152-year history. The dam failure and subsequent downcutting by the Chagrin River mobilized between 23,700 – 31,300 m^3 of sediment (9-13% of the original reservoir fill). It is difficult to separate the two processes (breaching and incision) because incision proceeded rapidly after breaching. However, it should be pointed out that the source of most of the sediment was due to incision, as the Chagrin River re-established

its hydraulic gradient across the reservoir. Of this volume of remobilized sediment, between 19,100 - 26,800 m³ (61-86%) was deposited in the downstream reservoir or Lower Mill Pond (Ohio Geological Survey, written communication 1994), and the addition of large volumes of fine-grained sediment to the downstream reservoir raised significant concerns about its safety (Baka 1994). The remaining between 3,820 - 5,350 m³ (14-39%) was deposited in the "floodplain" between the two reservoirs, which is actually chute channels in a meander loop (Ohio Geological Survey, written communication 1994). It is a concern that the continued erosion of sediment of the IVEX reservoir could accelerate the storage capacity loss of the downstream reservoir.

Damage Within the Reservoir

Flood effects within the IVEX reservoir include erosion that occurred during the dam failure (Fig. 7), de-



FIGURE 7. View of longitudinal scours produced in the reservoir due to escaping floodwaters after the dam breach. Person for scale (center background).



FIGURE 8. Compaction and desiccation of the fine-grained reservoir sediments following the dewatering of the reservoir. Shovel is 45 cm long.

commissioning of certain dams have shown that releases of fine-grained sediment would adversely impact water quality, change stream chemistry, modify substrate,

watering and subsidence of the muddy reservoir fill (Fig. 8), and slumping of the poorly consolidated reservoir sediments into the new channel of the Chagrin River (Fig. 9). Incision exposed bedrock cutbanks of the pre-reservoir channel (Fig. 10), white cedar stumps from the pre-1842 floodplain (Fig. 11), the upstream delta infilling the reservoir (Fig. 12), and examples of rhythmically-bedded, fining-upward sequences representing sequential floods over the interval 1842-1994 (Fig. 13). Core data could be used to identify specific flood horizons (Fig. 14), and calculate changes in sediment accumulation rates that occurred in the reservoir. These sedimentation rates, and corresponding changes in land-use and sediment conveyance within the drainage basin, are discussed in detail in Evans and others (2000a).

A number of studies have shown the importance of stabilizing the fine-grained reservoir sediment fill to prevent excessive sediment loadings downstream. For example, preliminary studies for proposed deliberate



FIGURE 9. Significant slumping of the water-saturated reservoir sediments into the newly incised channel of the Chagrin River as it adjusts to breaching of the dam and changes in longitudinal profile.



FIGURE 10. Bedrock outcrop exposed due to incision of the Chagrin River following breaching of the dam. This outcrop represents a bedrock valley wall of the pre-reservoir channel, being exhumed by recent incision.

or damage fisheries (Simons and others 1989; FERC 1991). In this case, observations in the days following the failure indicated that the Chagrin River rapidly incised to within a meter of the bedrock surface underlying the valley. At this point, the stream began to migrate



FIGURE 11. White Cedar stump from the pre-1842 floodplain forest, flooded and killed by the reservoir, and now exhumed by the dam failure. Shovel for scale is 45 cm.



FIGURE 12. New outcrop showing the delta at the upstream end of the reservoir. This deltaic distributary mouth bar consists of sand- and gravel-foresets with climbing ripple lamination. Shovel is 45 cm long.

laterally, however flow along the western side of the reservoir was already confined by bedrock valley walls. The threat is lateral channel migration eastward through the reservoir fill, which would erode these fine-grained materials.



FIGURE 13. Trench exposure of the reservoir sediments showing flood rhythmites (repetitive, fining-upward sequences of sand, silt, and clay with capping organic-rich laminae). Shovel is 1.5 m tall.

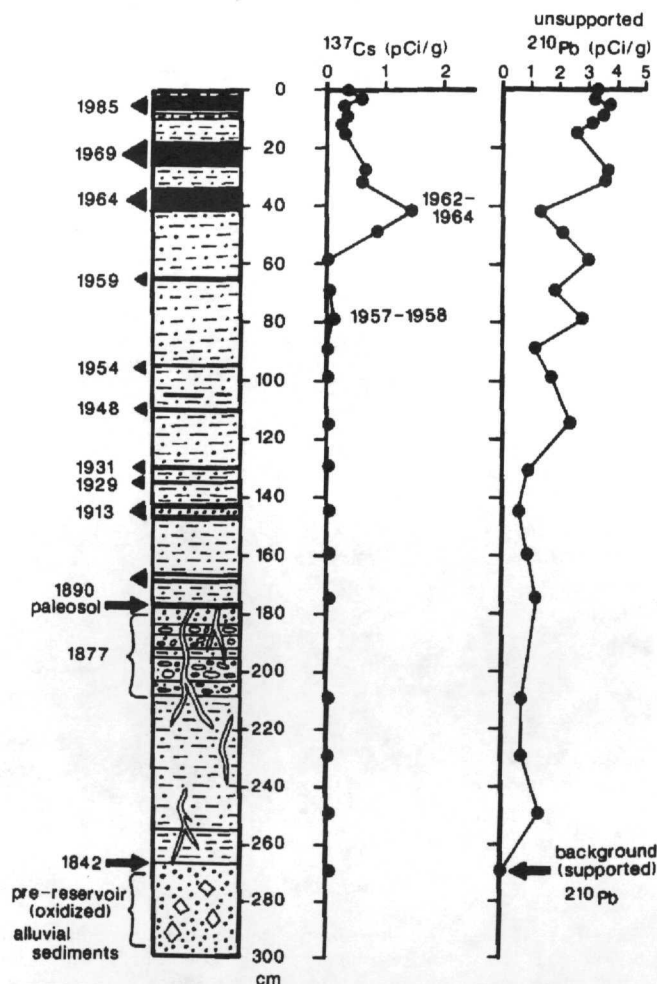


FIGURE 14. Data from core 94-IVEX-1A showing the core stratigraphy, activity of ^{137}Cs and activity of ^{210}Pb . A full discussion of assignment of ages to specific intervals is given elsewhere (Evans and others 1999A).

Storage Capacity Loss

The initial storage capacity of the IVEX Reservoir was estimated as 274,000 m^3 based upon historical data (ODNR 1987), field surveying by the Ohio Geological Survey, and our core data. Permanent pool capacity loss by time of dam failure was 86%, representing an annual storage capacity loss of 0.62% per year over the 152-year history of the structure (note: the 13 years between 1877-1890 are excluded from the calculation because the reservoir was dewatered at that time). These numbers are typical for reservoirs throughout the United States (Dendy and Champion 1978). Our core data permitted evaluation of capacity loss at specific time intervals, showing that annual loss rates varied from 0.37% per year to 1.72% per year (Table 1). This range of values is related to changing land-use practices within the drainage basin (which increased or decreased soil erosion rates) and also changing sediment conveyance rates due to episodic floods (Evans and others 2000a).

A question of interest is the sediment budget for this watershed. A sediment budget consists of input (soil erosion), intrabasinal storage (deposition of alluvium or colluvium within the basin), and output (sediment

yield, or the amount of sediment that leaves the watershed). An evaluation of soil erosion in the upstream drainage basin can be achieved using the Universal Soil Loss Equation (USLE). This procedure calculates soil loss (in mass per unit area) for specific types of land use, soil type, vegetation cover, slope angle, slope length, and rainfall intensity. Given the mix of such variables for the upstream drainage basin, we calculate upstream USLE soil loss of about 19,100 metric tons yr^{-1} for the IVEX reservoir.

The sediment yield can be obtained by calculating the mass of sediment in the reservoir, as corrected for the trapping efficiency of the dam. In order to convert sediment volume to mass, the volume must first be corrected for compaction (obtained from core data, this varies with depth, and averages about 30%), and multiplied by bulk density ($\rho_b = 1,620 \text{ kg m}^{-3}$). Accordingly, the total mass of sediment in the reservoir was found to be 246,000 metric tons, or an annual loading of 1,770 metric tons yr^{-1} (again, years 1877-1890 are excluded from the calculation). The trapping efficiency of the IVEX dam is estimated at 67%, based upon the comparison of the sediment load trapped in the IVEX reservoir versus the lower reservoir, and the approximately 90% trapping efficiency of both structures acting together. Thus, the sediment yield indicated by the IVEX reservoir is 2,350 metric tons yr^{-1} and the sediment delivery ratio (sediment yield divided by soil erosion rate) is 12.3%. This figure is bracketed by empirical calculations based upon other reservoirs (9.6% according to the method of Brune 1953) and studies on soil erosion rates (15% according to the method of Boyce 1975). These numbers indicate that most (87.7%) of detached soil particles are deposited in the basin as intrabasinal storage pending increases in sediment conveyance rates, such as major storms (Evans and others 2000a). Field observations indicate significant colluvium storage in this region.

DISCUSSION

A dam failure offers numerous instructive lessons. The first is conceptual—the recognition that dams are, in fact, unnatural and short-term features in a landscape. Theoretically, a well-designed and well-maintained dam can be operated indefinitely. In practice, thousands of the oldest dams in the US were not designed using modern hydrological principles. In these cases, the combined effect of storage capacity loss, inadequate spillway design, and lack of emergency spillways can convert dams and reservoirs from flood control assets to liabilities. For such dams, the life expectancy is a function of its storage capacity loss, and thus a dam is considered at the end of its useful life when about 60% storage capacity loss occurs (Hahn 1955). Given typical loss rates of 0.5-1.0% storage capacity loss per year, these older dams have an average life history of about 60-120 years (Hahn 1955; Dendy and Champion 1978). The magnitude of the problem becomes apparent when considering that, by 2020, greater than 85% of the dams in the US will be near the end of their operational lives (FEMA 1999). Many of the older dams were

TABLE 1

IVEX reservoir storage capacity loss.

	1842- 1877	1890- 1913	1913- 1931	1931- 1948	1948- 1959	1959- 1969	1969- 1989	1989- 1994
Years Record	35	23	18	17	11	10	20	5
Interval Thickness (m)	0.98	0.32	0.41	0.33	0.28	0.27	0.32	0.14
% Core Length	32.1	10.5	13.4	10.9	9.0	8.9	10.4	4.7
Interval Porosity	0.45	0.50	0.55	0.57	0.59	0.62	0.64	0.70
Decompacted Interval Thickness (m)	1.64	0.48	0.56	0.44	0.35	0.33	0.37	0.15
Interval Sediment Volume (10^4 m ³)	103	14.7	35.4	27.7	22.3	20.7	23.6	9.7
Interval Storage Capacity Loss (%)	60.3	8.6	20.6	16.1	12.9	12.0	13.7	5.6
Annual Storage Capacity Loss (%)	1.72	0.37	1.14	0.95	1.18	1.21	0.69	1.12
Sedimentation Rate (cm yr ⁻¹)	4.69	2.09	3.11	2.59	3.18	3.30	1.85	3.00
Mass Sedimentation Rate (g cm ⁻² yr ⁻¹)	4.68	2.58	3.81	3.27	4.19	4.55	2.65	4.77

originally built for hydropower, and were later converted for different purposes. This may or may not impact dam safety, but in the case of the IVEX dam such conversion (hydropower to water supply) appears to coincide with less active dam maintenance. This was manifested in growth of trees on the earth-fill dam, untended seepage problems on the dam and spillway, and poor maintenance of drains and other structures (ODNR Division of Water 1987).

A second lesson is that dam failures represent more than one threat of damage. The most obvious threat is the floodwave generated by sudden breaching of the dam. This can result in direct damage due to submergence, hydraulic damage, and loss of life or property damage. A less obvious threat is sedimentation, due to the mobilization of the fine-grained sediment trapped in the upstream reservoir. In the case of the IVEX failure, the most serious damage downstream, long-term, is the influx of fine-grained sediment into the downstream reservoir. In other words, in this case failure of an upstream structure threatens the integrity of a downstream structure.

A particular problem facing the dam owners, regulatory agencies, and local population following a dam failure is whether or not to rebuild the structure. This is an expensive proposition, because breaching failure can undermine all of the structure, requiring removal of the surviving portions of the dam prior to rebuilding. The cost of rebuilding the IVEX dam was estimated at \$1-2.5 million. However, site remediation poses significant problems even if the dam is not rebuilt. The major problem is how to stabilize the fine-grained reservoir sediments to prevent siltation problems downstream. In the case of the IVEX dam, an experimental program is

taking place to convert the former reservoir into a riparian wetland, and use plant growth to stabilize the reservoir muds (Evans and others 2000b).

A final lesson from a dam failure is that they are opportunities to recover significant information about the effect of humans on a landscape. Dewatered reservoirs are exceptional geological laboratories to recover information and artifacts giving insights to the historical development and changes in the watershed, and to interactions between human activities and hydrological, geological, and ecological change. It is not only possible to evaluate the magnitude of changes from pre-settlement times until today, but also to consider choices about future conditions. A dam failure forces recognition that, despite their longevity in human terms, these structures are short-term features in the landscape.

SUMMARY AND CONCLUSIONS

The failure of the IVEX dam on 13 August 1994 should have been anticipated, given its age, storage capacity loss, and history of management problems. Older dams, with inadequate primary spillways and lack of emergency spillways, are vulnerable to failure due to storage capacity loss due to sedimentation. An evaluation of core data shows that storage capacity loss varied from 0.37% to 1.72% per year, culminating in 86% storage capacity loss over the 152-year history of the dam. It is widely accepted that 60% storage capacity loss terminates the usefulness of such dams and reservoirs, and converts a dam from an asset to a flood control liability.

The IVEX dam failure was the result of seepage piping problems that had been recurrent over a long interval of time. Simple management practices, such as clearing the dam of trees or screening the spillway from large

logs, were not followed. The spillway design was inadequate, and there was no emergency spillway. Data from FEMA show that many thousands of dams in the US suffer from lack of maintenance or adequate monitoring. Ironically in this case, the vulnerability of the structure was accurately predicted in a dam safety inspection seven years prior to failure, but no remedial action was taken. This suggests that lack of enforcement may be a significant problem for dam safety.

The dam breach resulted in a floodwave that had stage height of at least 1.5 m above bankfull depth at a distance about 200 m downstream of the dam, and a peak discharge of about 466 m³ sec⁻¹. The flood caused hydraulic damage, flooding, and sedimentation problems downstream. The floodwave entered and crossed a downstream reservoir, and caused notable erosion and inundation damage 7.0 km downstream. However, the most serious problem was not the flood itself, but long-term effects of release of fine-grained sediment formerly impounded behind the dam. There are no simple solutions to sediment management, although in this case an experiment is being conducted to remediate the former reservoir as a riparian wetland, using aquatic vegetation to stabilize the reservoir sediments. Dam failures offer both problems and opportunities, and force recognition on the transient nature of dams, and their liabilities as well as benefits.

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